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FRACTURE CHARACTERIZATION OF PVC FOAM CORE SANDWICH SPECIMEN USING THE DCB-UBM TEST METHOD

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ABSTRACT

Face/core debond failure in sandwich composites is a critical failure mode. Lack of cohesion between face and core will lead to loss of structural integrity. The estimation of interface fracture toughness especially at the face/core interface is extremely challenging, provided the dissimilarity of material properties across the interface. The crack path and fracture also depend on the loading configuration at the crack tip. Depending on the type of loading applied, a measure of shear deformation at the crack tip is expressed by the mode-mixity phase angle (ψ). A suitable fracture mechanics approach coupled with experimental validation is paramount to determine the fracture resistance of the face/core interface. In this paper, the test-rig exploiting the double cantilever beam with uneven bending moments (DCB-UBM) concept is used to determine the fracture toughness of PVC foam core sandwich composites. The DCB-UBM test enables fracture testing over a large range of mode-mixities as expressed by a phase angle (ψ) which is a measure of the amount of shear loading at the crack tip. A desired phase angle may be achieved by changing the moment-ratio ($MR = M_d/M_s$).

1 INTRODUCTION

Fracture testing of PVC H45 foam cored sandwich specimens was performed using the double cantilever beam-uneven bending moments (DCB-UBM) concept to determine the fracture toughness under mixed mode (I/II) conditions. The DCB-UBM test method was first introduced by Sørensen et al. [1] for fracture testing of laminate composites. This was extended to fracture testing in sandwich composites by Østergaard et al. [2] and Lundsgaard-Larsen et al. [3]. The DCB-UBM test rig (refer to Figure 1) enables fracture testing over a large range of mode-mixity phase angle (ψ), which is a measure of the amount of shear loading at the crack tip. A desired phase angle may be achieved by changing the moment-ratio (MR) which is the ratio of the two moments applied at the pre-crack edge. Pilot studies were also conducted to perform fracture characterization of honeycomb core sandwich specimens, in predominant mode I conditions using the DCB-UBM test methodology [4].

Closed form expressions for mode-mixity phase angle and energy release rate for a DCB-UBM sandwich specimen was provided by Kardomateas et al. [5]. The mode-mixity phase angle (ψ) in [5] is expressed in terms of a scalar quantity, ω. The scalar quantity need to be obtained only once for a typical sandwich configuration using a numerical mode-mixity method. Furthermore, the DCB-UBM sandwich specimens are reinforced with stiff layers in order to reduce the face sheet lift off. Under such circumstance, the phase angle (ψ) needs to be determined numerically. The finite-element based mode-mixity method; Crack Surface Extrapolation Method (CSDE) [6] is utilized here to identify the moment ratio (MR) which corresponds to the desired phase angle (ψ).

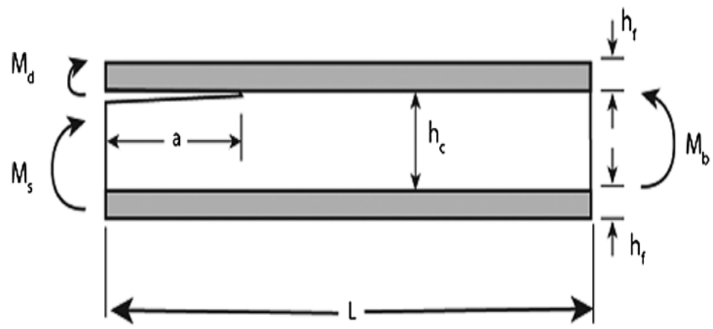

Figure 1: a) Principle of DCB-UBM test

2 DCB-UBM TEST RIG

Schematic illustration of the test rig with specimen mounted prior to testing is shown in Figure 2. Two independent hydraulic actuators are used to apply rotation on both arms. The actuators are controlled using the MTS FlexTest SE™ controller. As discussed before, the DCB-UBM test method enables application of moment on crack flanks with a pre-determined moment ratio (MR). In order to implement such a control algorithm on the actuators, a CASCADE program is implemented. The fracture tests are carried out at rotation control and prior to start of the test the MR is given an input to the controller.

Torque load cells are mounted on top of each actuator to measure the applied moments. In addition, angular displacement transducer is also fixed on the actuator to measure the rotation of each arm. To surmise, the load cell, actuator and angular displacement transducer are connected in series for each arm. The load and rotation are recorded at 10 Hz during the test. A rotation command of 10 deg/min is supplied to arm 1. The pre-crack is between the two crack flanks, where arm 1 refers to the flank with top face sheet and doubler laer. The control algorithm is programmed such that arm 2 follows arm 1 with a moment ratio (MR), which is provided before the start of the test. The test is manually stopped when the crack propagates more than 20 mm. The algorithm is implemented in MTS TestSuite Mulitpurpose Elite™ program, which is also used to gather and store data. To ensure that there are no vertical forces in the specimen, rolling support is provided on the specimen end (see Figure 2). When crack propagates, the specimen slides forward preventing any build-up of transverse force.

The sandwich specimens are reinforced with stiff layers to prevent large rotation of the crack flanks. This unique specimen design was first employed by Lundsgaard-Larsen et al. [3] to extract cohesive laws of a foam core sandwich specimen. The selection of such “doubler” layers should be such that, they do not undergo yielding during testing. This ensures that the whole fracture analysis is carried out in the Linear Elastic Fracture Mechanics (LEFM) regime. Doubler layers made from high strength; Uddeholm IMPAX SUPREME steel grade is chosen here with a thickness of 6 mm. The steel layers are adhesively bonded to the face sheets using Araldite 2015 epoxy based adhesive system. Moreover, a stiff layer makes it easier to apply moments on both arms. The specimen is slid between the loading arms (see Figure 2). The sandwich specimen is composed of 6 mm thick glass fiber face sheets and a 30 mm thick H45 foam core. It should be noted that, for the DCB-UBM test method there does not exist a standard data-reduction method to compute fracture toughness. A J-integral expression was derived for a reinforced sandwich specimen by Lundsgaard-Larsen et al. [3]. Since the fracture testing carried out here is in the linear elastic regime, this expression can be utilized to the compute energy-release rate for any moment couple magnitude. An alternative data-reduction scheme for static analysis is derived and presented here.

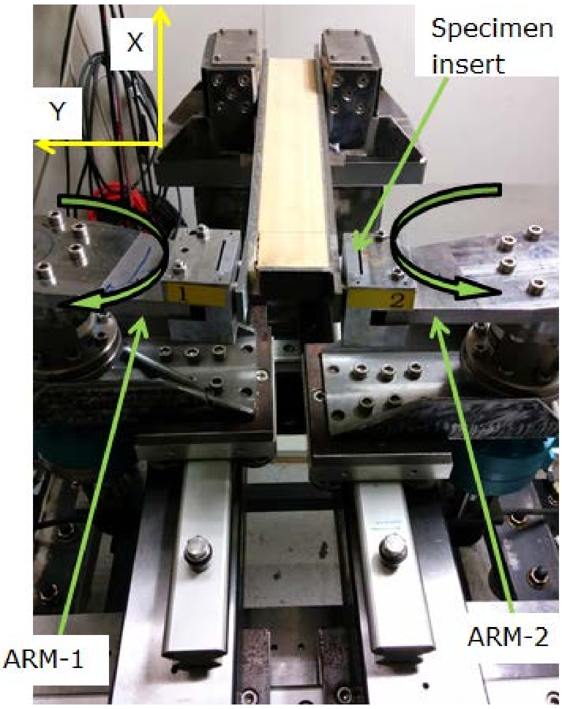

Figure 2: DCB-UBM test fixture with an E-glass/H45 sandwich specimen.

2.1. Data reduction method for static analysis

The moment and rotation of each arm is recorded during the test and can be used to compute the energy-release rate. Now, the moment on each arm can be expressed as:

$$M = \frac{EI\theta}{a} \tag{1}$$

where θ is the rotation of the crack flank. The strain energy release rate is expressed as the net energy between stored elastic strain energy and the work provided by external forces.

$$G = \frac{-d}{da}(W - U) \tag{2}$$

When the external work supplied is zero, fracture energy at the interface corresponds to the elastic energy stored:

$$\delta \mathrm{U} = \frac{\theta \delta M}{2} \tag{3}$$

Therefore, for a single beam the strain energy release rate is given as:

$$G = \frac{d}{dA}(\delta \mathrm{U}) = \frac{\theta dM}{2dA} \tag{4}$$

where $dA = B.da$. The compliance term for the DCB-UBM specimen is defined using rotation and moments as:

$$c = \frac{\theta}{M} = \frac{a}{EI} \tag{5}$$

The strain energy release rate obtained for a single beam from Equation (4) as:

$$G = \frac{\theta^2}{2c^2}\left(\frac{dc}{dA}\right) = \frac{M^2}{2}\frac{dc}{dA} \tag{6}$$

The critical energy release rate for the two beams is then given by:

$$G_c = \frac{1}{2A}\left[\frac{M_{1c}^2}{(EI)_1} + \frac{M_{2c}^2}{(EI)_2}\right] \tag{7}$$

where M_c is the critical moment which initiates crack propagation. The critical moment is identified from a plot of M *vs* θ as the departure from the slope.

3 MIXED-MODE FRACTURE TESTS: RESULTS AND DISCUSSION

The fracture test is carried at a constant angular velocity of 10 [deg/min] while measuring the resulting moments in each arm. A numerical mode-mixity method, the Crack Surface Displacement Extrapolation (CSDE) method is utilized to identify phase angles vs. moment ratio (MR) for the E-glass/H45 sandwich specimens. It was found that a MR values of -10, 7.5 and 1.0 corresponds to phase angles ψ = -13.3°, -26.4° and -64.1° respectively, reflecting predominant mode I, mixed-mode and predominant mode II regimes. A total of three specimens are utilized for testing. One of the advantages of the DCB-UBM test method is the ability to re-use the specimen. For instance, a specimen which was tested at a fixed moment ratio (MR) can be used to perform another test with a different MR, provided the crack has not reached the end of the specimen. For most DCB-UBM test cases, the test is stopped once the crack has propagated ~ 20 mm. However, in the current test campaign, three test specimens were used.

As described earlier, the controller ensures that the moment ratio is kept constant throughout the test. A plot of moment ratio (MR) vs rotation of the debonded face sheet is provided in Figure 3. Perturbation in MR during the initial stage of test was observed for the MR cases 7.5 and -10. This happened during the initial stages of testing and did not affect the crack propagation. The crack propagation happened outside this window (for $\theta > 3°$), where the MR is kept nearly constant (see Figure 3). Crack propagation was observed to happen along the face/core interface for all the specimens evaluated.

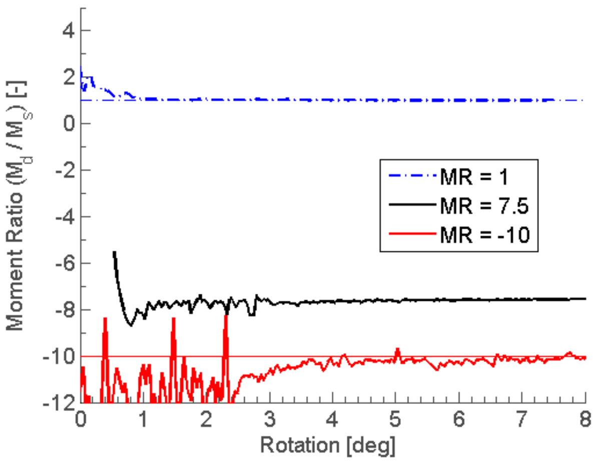

Figure 3: Moment ratio, MR vs rotation of debonded face sheet, MR = 1, 7.5 and -10 (E-glass/H45) sandwich specimen.

A plot of moment vs rotation of the debonded arm obtained for the three cases is shown in Figure 4. The critical moment can be identified as the departure from the slope of the moment vs. rotation curve and is highlighted on the plot with a star symbol. A steep rise in slope is observed during the loading phase. Once the crack propagation is initiated, the moment values deviate and a steady state regime is reached as seen in Figure 4. The critical moments were substituted in Equation (9) to obtain fracture toughness (G_c) values.

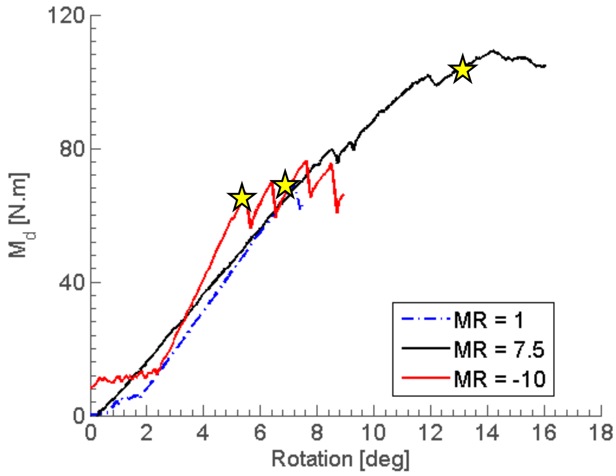

Figure 4: Moment M_d vs rotation of the debonded face sheet (E-glass/H45) sandwich specimen with h_f = 6 mm and h_c = 30 mm.

For all cases of MR values tested here, the crack propagated along the face/core interface. A stick-slip behaviour was observed when the crack propagated in predominant mode II conditions (MR = 1). This phenomenon can be attributed to the relatively soft PVC H45 core. A typical face/core interface crack propagation for E-glass/H45 sandwich specimen is shown in Figure. 5 for MR = 7.5 (ψ = -26.4°). It is also noted that, crack kinks into the core as it approaches specimen end. This may be due to the edge effects that influences the crack tip mode-mixity. Fracture toughness data obtained for the three cases varied in the range from 225 – 600 [J/m^2]. As expected, the data shows a strong dependency fracture toughness on the mode-mixity phase angle.

Figure 5: Crack propagation along face/core interface for an E-glass/H45 sandwich specimen, loaded with MR = 7.5.

4 CONCLUSIONS

The double cantilever beam loaded with uneven bending moments (DCB-UBM) was employed to perform mixed-mode fracture testing of PVC H45 foam core sandwich specimen. The moment ratio remained nearly constant throughout the test except for initial perturbation. Crack propagation was observed to occur in the face/core interface. A closed form expression to compute the energy release rate as a function of recorded moments was presented and utilized for data reduction. The interface fracture toughness was obtained from the energy release rate expression by substituting critical moment values. The critical moment value is obtained from the plot of moment vs. rotation. The fracture toughness was observed to vary with mode-mixity phase angle.

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